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The DS1 Hyper-Extended Mission

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The Primary Mission for Deep Space 1 (DS1) was to demonstrate 12 new technologies one of which was the Ion Propulsion System (IPS). After successfully completing its primary mission, DS1 was given a new mission. The objective of this Extended Mission was to fly by the Comet to Borrelly. After the successful Borrelly encounter, the ion thruster on DS1 had be operated for more than 14,000 hours in space. This provided a unique opportunity to investigation the condition of the thruster after long-term operation in space and determine, to the extent possible, if the thruster wear in space is consistent with that observed in long-duration ground tests. The DS1 Hyper-Extended Mission was designed to perform a series of tests to investigate the conditon of the DS1 ion thruster. These tests included a "plume mode survey" to map out the operating characteristics of the neutralizer cathode; perveance and electron-backstreaming tests to determine the extent of accelerator grid aperture erosion; direct thrust measurements to compare to similar measurements made earlier in the mission and before flight; discharge chamber performance curves; measurements of the magnetic field produced by the thruster's permanent magnets; and the impact of thruster-produced charge-exchange plasma on the solar array. The results of theses tests are described herein.

Introduction

NASA's Deep Space 1 (DS1) mission was the first use of ion propulsion for primary propulsion on a deep space mission and successfully validated this technology for future science missions [1]. The ion propulsion system (IPS) on DS1 was first used to provide the DV necessary for the spacecraft to fly by the asteroid Braille. After successfully completing its primary mission of demonstrating new technologies DS1 was redefined as a science mission with the objective of flying by the comet Borrelly [2]. This Extended Mission was successful~~ly~~ in September 2001. At this time the ion thruster had been operated for more than 14,000 hours in space.

This was by far the longest any ion thruster had ever been operated in space and represented a unique opportunity for NASA to evaluate the extent to which long-duration operation and thruster wear in space agreed with that expected based on ground life tests and analyses of the key wear out mechanisms. Therefore NASA executed what became known as the Hyper-Extended Mission for DS1. This mission was designed to evaluate key characteristics of the ion engine performance after extended operation in space. This paper describes the results of this evaluation. At the end of the Hyper-Extended Mission, the ion engine on DS1 accumulated 16,265 hours of operation and processed approximately 72 kg of xenon.

Approach

It is possible to obtain significant information about the health of ion thruster from its electrical characteristics. Measurements of the perveance and electron-backstreaming characteristics provide information about the erosion of the accelerator grid

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apertures. Both the perveance margin and the magnitude of the accelerator voltage increase as the accelerator grid apertures enlarge as a result of erosion by CEX ions, providing two different methods for measuring the increase in accelerator grid aperture diameters. Discharge chamber performance curves and direct thrust measurements can provide information about the doubly charged ion content in the beam. The suite of diagnostics on DS1 provide information about the health and operating modes of the neutralizer.

Background and DS1 Flight History

The ion thruster that flew on DS1 is designed for solar electric propulsion (SEP) applications and therefore can be throttled over a wide range of thruster input powers (from 469 W to 2325 W at end of life). This throttle range is divided into 112 discrete steps called "mission levels" (ML). The thruster input power varies by an average of 17 W between each ML. The mission levels are grouped into 16 distinct "throttle levels" (TH), resulting in 7 MLs in each throttle level. Each TH has a fixed set of flow rates and beam current. The MLs in each TH are obtained by varying the beam voltage with the beam current fixed at the value specified for the TH as indicated in Fig. 1. The end-of-life (EOL) values for the 16 throttle levels and all 112 mission levels are given in Table 1. The EOL thrust and total flow rate at each ML are shown in Fig. 2.

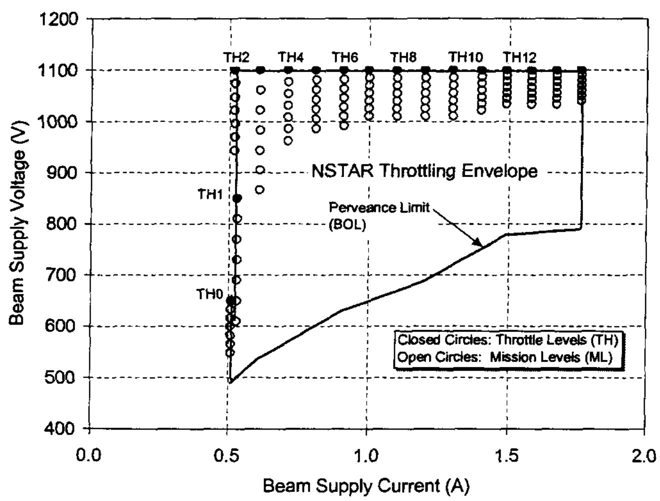

Fig. 1 DS1 throttle envelope.

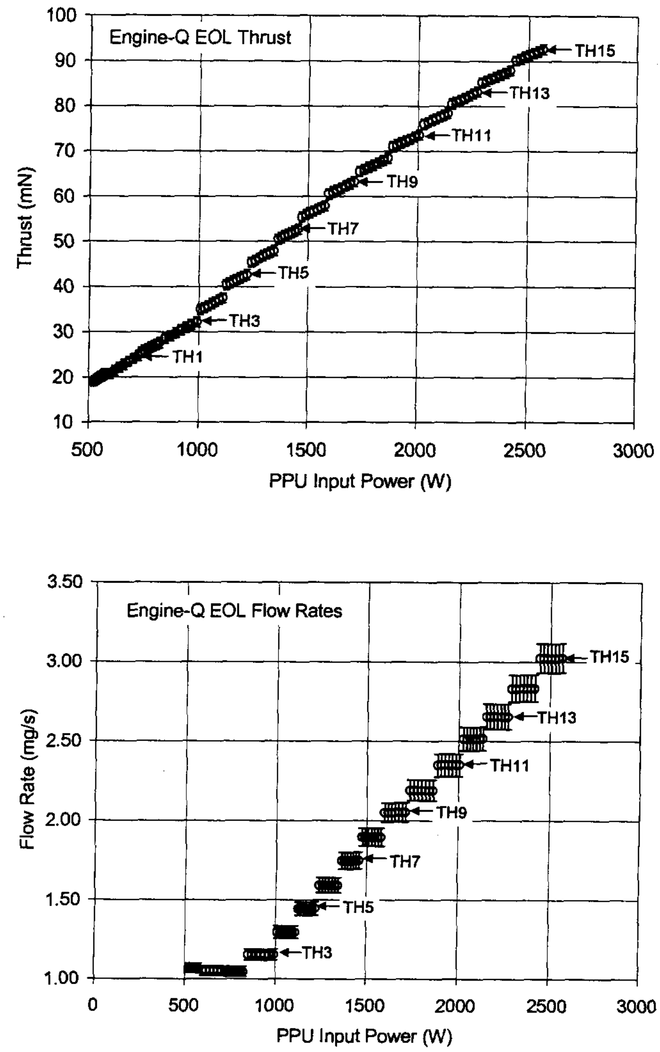

Fig. 2 End-of-life thrust (top) and flow rate at each mission level.

Primary Mission

During DS1's Primary Mission, there were two planned sets of tests designed to characterize the performance of the ion propulsion system (IPS). These were call Ion Acceptance Test 1 and 2 (IAT1 and IAT2). The results of these tests are summarized in Polk, et al. [ref].

Extended Mission

Following the flyby of the asteroid Braille, IPS thrusting was resumed to put the spacecraft on a trajectory to encounter the comet 107P/Wilson-Harrington [Rayman]. After nearly three months of thrusting a coast period began on October 20, 1999. At that point, the IPS had consumed 21.6 kg of the

81.5 kg of xenon onboard at launch, imparted 1.32 km/s to DS1, and completed 3571 hours of operation.

Failure of the stellar reference unit in November, 1999 required an immense amount of work to rewrite the flight software to use the MICAS camera in place of the failed start tracker. Development, testing and implementation of this new software took almost eight months. In July 2000, the spacecraft was once again ready, willing and able to support IPS operation. This time, however, with an additional duty.

Recovering from the star tracker failure consumed much more of the hydrazine propellant used for attitude control than if there had been no failure. Indeed, there was insufficient hydrazine to maintain attitude control until the planned September 2001 encounter with the comet Borrelly and execute the required trajectory correction maneuvers just prior to the encounter. There was, however, plenty of xenon on board. Consequently, the DS1 operators decided to use the ion thruster to provide pitch and yaw control of the spacecraft even when IPS thrusting was not required for the trajectory (roll control was still provided by the hydrazine reaction control system). This strategy saved enough hydrazine to be mission enabling and the DS1 Extended Mission, which had been reclassified as a science mission, was back on track.

Operation at low power levels (ML10 to ML20) provided sufficient control authority, while consuming a minimum amount of power and xenon. Because attitude control is required all the time for at 3-axis stabilized spacecraft, it was necessary to operate the ion thruster almost all the time. After recovery from the start tracker failure in July 2000 to the end of the Hyper Extended mission in December 2001, the IPS duty cycle (the fraction of real time that the IPS is operating) was greater than 99%. As a result, the ion thruster accumulated a substantial number of operating hours, most of which was at low power levels.

Change in Neutralizer Behavior. In April 2001, after the thruster had accumulated approximately XX,XXX hours of operation, Brinza identified a change in the characteristics of the RPA traces taken routinely during each thruster start. A gradual increase was observed in the ion current collected by the RPA at a fixed thrust level. Review of data indicated very minor increase started in March. Comparison of IPS ML10 starts in December 2000 vs. May 2001 show a change in ion current about 6 hours after start-up. Figure 3 shows the ion current measured by the RPA during three starts to ML10 in December 2000. The thruster startup procedure sets the main flow rate at the TH0 level, and the cathode and neutralizer flow rates are set to their full power values (TH15). After thruster ignition, the cathode flow rates are returned to the desired run values. If the thruster is to be operated at low power, such as ML10, the cathode flow rates must be decreased significantly. The design of the xenon feed system [Gani ref.] results in a fairly lengthy time to accomplish this change in flow rates -- on the order of 6 hours. The decrease in ion current measured by the RPA in Fig. 3 results from the increase in discharge chamber propellant efficiency as the cathode flow rate decreases to its ML10 set point.

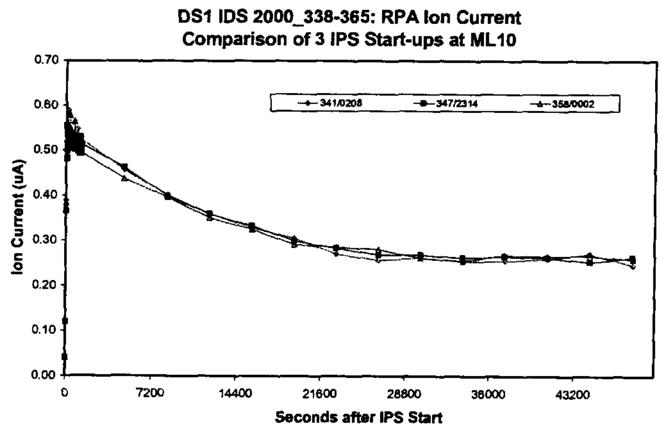

Fig. 3 RPA ion current during three thruster starts to ML10 in December 2000.

The ion current measured by the RPA for eight thruster starts to ML 10 in March and April 2001 are shown in Fig. 4. These data show the characteristic decrease in ion current until about 6 hours after start when an abrupt increase in current is observed. In addition, these data indicate that the later starts have a larger increase in current.

Examination of RPA energy sweeps revealed higher-energy ion distributions as well as increased ion currents roughly 6 hours after startup. Increased in noise measured by the Plasma Wave Antenna also correlated with the RPA ion energy increase. Neutralizer "plume-mode" operation was identified as leading cause.

"Plume-mode" operation is characterized by an ionization region that extends downstream of orifice producing a plasma with a higher electron temperature and increased ion energies. Operation under severe plume-mode conditions is known to result in increased cathode erosion rates. Cathode failures have been observed as a result of prolonged operation in this mode. Since extended IPS operations were required to reach the comet Borrelly, it was decided to increase the neutralizer flow rate to return its operation to the desired "spot-mode" condition.

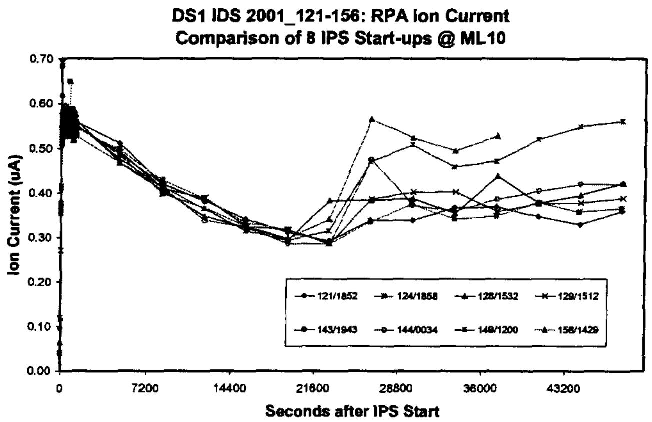

Fig. 4 RPA ion current for eight thruster starts to ML 10 in March and April 2001.

A 20% increase in neutralizer flow was recommended by the IPS team, from 2.4 to 2.9 sccm. A throttle table was successfully loaded on July 10, 2001. RPA ion current have remained stable and at predicted levels since the new table load.

At the end of the Extended Mission, the ion thruster on DS1 had been operated for more than 14,000 hours. A plot of the power level vs. operating time though the end of the Extended Mission is given in Fig. 5.

Planned Tests

The following series of tests were planned to investigate the condition of the DS1 ion engine after more than 15,000 hours of operation in space.

Neutralizer Plume Mode Survey

As a result of the observed change in neutralizer operating characteristics during the Extended Mission, the neutralizer plume mode survey (PMS) was designed to provide a more detailed investigation of the effect of flow rate and keeper current on neutralizer operation. The plan was to operate the thruster at ML6 (TH0) and then operate the neutralizer with flow rates of 3.0, 2.7, 2.4, 2.2 and 2.0 sccm. The IPS xenon feed system flow control is determined by plenum tank pressure [Gani ref]; so reducing flow rate requires bleed-down of the plenum, a slow process. The neutralizer and cathode flow rates are coupled in the DS1 xenon feed system [Gani ref] so reducing the neutralizer flow rate also reduces the main cathode flow rate. At constant beam current, this process results in thruster operation over a range of discharge chamber propellant utilization efficiencies. Consequently, a side effect of the PMS procedure is that a discharge chamber performance curve is obtained.

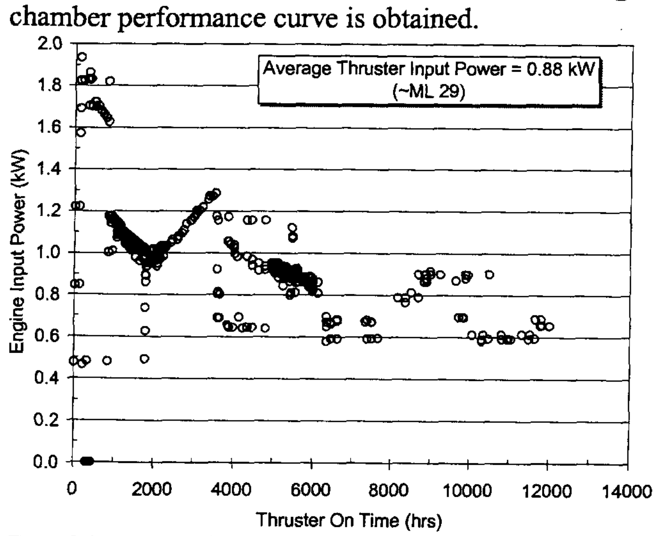

Fig. 5 History of thruster operating power levels on DS1.

Once the target neutralizer flow rate is achieved, the neutralizer keeper current is varied at 3-minute step intervals. Neutralizer keeper currents were varied from 2.4 A down to 1.6 A at each flow rate. An example of this process for flow rates of 2.2 sccm and 2.0 sccm is given in Fig 6. RPA sweeps were recorded at each combination of flow rate and keeper current. If the neutralizer keeper voltage exceeded a preset limit, the tests at that flow rate were terminated and the process was repeated at the next planned flow rate.

Ion Optics Tests

A series of ion optics tests were planned to investigate the extent of accelerator grid aperture erosion. Enlargement of the accelerator grid apertures by charge-exchange (CEX) ion erosion will change the perveance and electron-backstreaming (EBS) characteristics of the ion accelerator system.

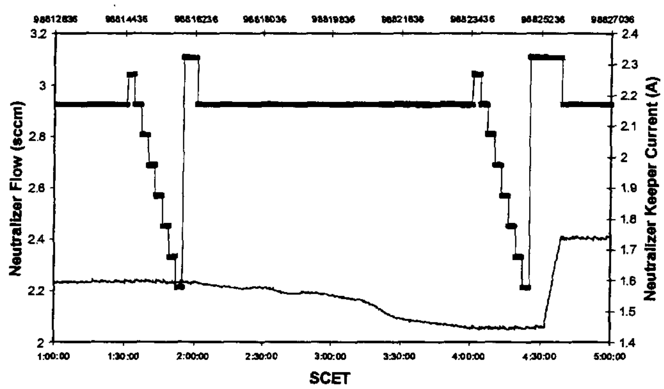

Fig. 6 Example of how the neutralizer keeper current and flow rate were varied during the plume mode survey (for 2.2 sccm and 2.0 sccm).

Measurement of the perveance requires reducing the beam voltage at a fixed beam current until the accelerator grid current increases. Since the spacecraft was too far from Earth to command this process in real time, it was necessary to develop an automated sequence which would determine the perveance limit without undo risk to the thruster. The process used was to decrease the beam voltage initially in relatively large steps where there was a high degree of confidence that the accelerator system would be far from the perveance limit. As the expected perveance limit was approached the incremental change in beam voltage was decreased to 1 V. This process was continued until the accelerator grid current exceeded 4 mA. It was planned to obtain perveance data at two different beam currents corresponding to the operating points at TH0 and TH3. There was insufficient power from the solar array to perform this test at higher beam currents.

A similar process was followed to determine the electron-backstreaming limits. In this case, there was greater concern that the thruster could be damaged as a result of extended operation in a backstreaming condition. To find the electron-backstreaming limit beam current and voltage were held constant and the magnitude of the accelerator grid voltage was decreased, initially in large increments and subsequently in 1-V increments, until the discharge current decreased by XX % from it nominal value.

Ion Acceptance Test 3 (IAT3)

The objective of this test was to directly measure the IPS thrust for comparison with a similar series of tests (IAT2) performed much earlier in the mission (in May 1999). The thrust is measured by looking at the Doppler shift in the downlink signal as described by [ref]. The plan called for thrust measurements to be made at ML6, ML13, ML20 and ML 27. During IAT2 in 1999 thrust measurements were also made at ML34, but there was insufficient power from the array to operate at this mission level during IAT3 (due to the spacecraft's greater distance from the sun). Additional tests were added to IAT3 to investigate:

- The effects of doubly-charged ions at high propellant utilization on the measured thrust. This test was performed by starting at ML20 and increasing the beam current in six steps (with 10 minutes at each step) from 0.52 A to 0.61 A at constant flow rate, resulting in increase in discharge chamber propellant utilization from 81% to 95% (uncorrected for double ions).
- Operate at low propellant utilizations to facilitate correlations with ground tests. For these tests the IPS was operated at beam currents and voltages appropriate for mission levels 6, 13, 20 and 27, but with significantly higher flow rates (corresponding to ML55 and ML83)
- Characterize the beam voltage/current envelop around ML20-27. The IPS was set to ML27 with a low beam voltage (500 V). The beam voltage was then increased in steps of 150 V at 10-minute intervals up to 1100 V.
- Assess current collection by the SCARLET solar array for different positions of the array relative to the ion thruster. With IPS operation at ML6 beam current and voltage, but with ML83 flow rates, the plan was to execute a slow spacecraft turn to change the relative angle of the solar array with respect to the thruster. Operation at high propellant flow rates was expected to maximize the production of charge-exchange ions to maximize the interaction of the CEX plasma with the solar array.
- Gimbal the thruster and characterize the variation in magnetic field measured by the IDS magnetometer.

Diode Mode

At the beginning of the DS1 Primary mission in November 1998, the first test of the ion thruster was the diode mode test in which the thruster is operated with the neutralizer and main discharges operating, but without beam extraction. At the end of the

Hyper-extended mission in December 2001, the diode mode test was repeated in order to compare to the original test. This was the last test performed on DS1.

Hyper-Extended Mission Results

A list of actual tests performed during the Hyper-extended Mission is given in Table 2.

Neutralizer Plume Mode Survey

The PMS tests to characterize DS1/IPS neutralizer operation under low-flow conditions were performed on October 23, 2001 and on December 10-11, 2001. The initial test sequence operated as expected until the it was aborted at the minimum flow rate (2.0 sccm) by tripping the neutralizer keeper voltage limit. The test was repeated and successfully completed on December 10-11 with less conservative limits on the keeper voltage.

The variation in neutralizer keeper voltage and neutralizer common voltage (which is the voltage between the neutralizer common line and spacecraft ground) obtained during the PMS are given in Figs. 7 and 8, respectively. These data indicate no unusual behavior of the neutralizer. The neutralizer keeper voltage increases as the flow rate is reduced as one would expect and shows little variation with keeper current at a given flow rate. The neutralizer common voltage data in Fig. 8 indicates essentially no differences between the flow rates.

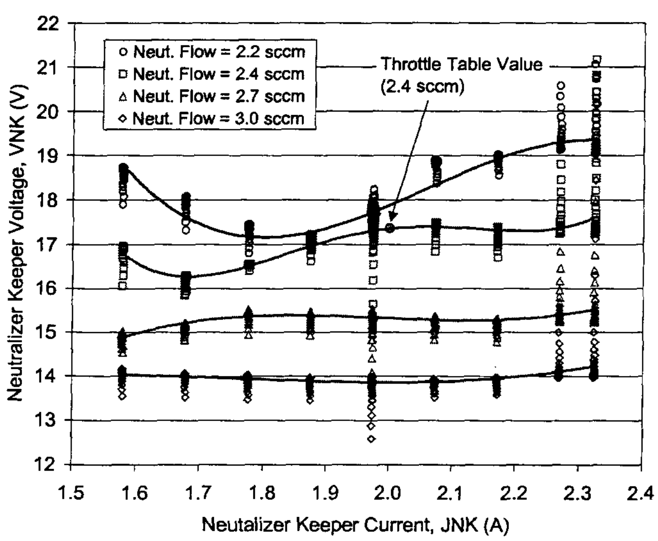

Fig. 7 Neutralizer keeper voltage during the plume mode survey.

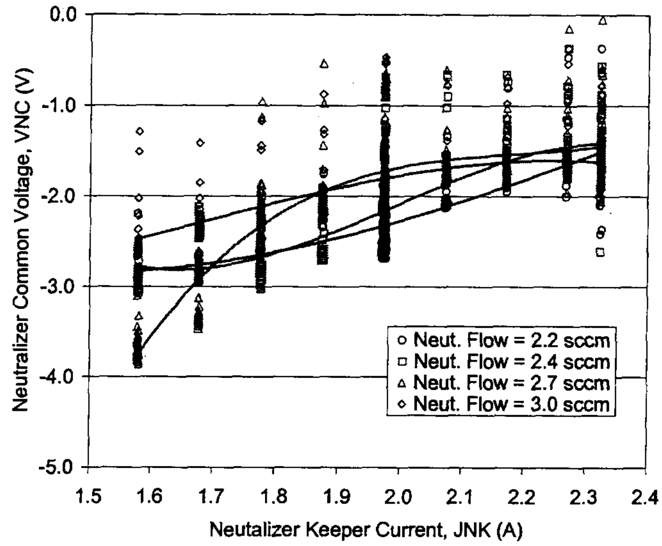

Fig. 8 Neutralizer common voltage during the plume mode survey.

The IDS RPA data, however, observed high-energy ions and increased ion flux as the neutralizer transitioned into "plume-mode" operation at the lower flow rates. Data for neutralizer flow rates of 3.0, 2.7, 2.4 and 2.2 sccm are given if Figs. 9-13, respectively. The transition to plume mode at 2.2 sccm occurs at a neutralizer keeper current of about 2.1 A. AT 2.4 sccm this transistion occurs at 2.0 A. There is no transition to plume mode over the range of keeper currents tested at a flow rate of 3.0 sccm. For the minimum flow rate tested (2.0 sccm), the neutralizer operated in or near plume mode conditions for all neutralizer keeper currents except the highest value, 2.4A.

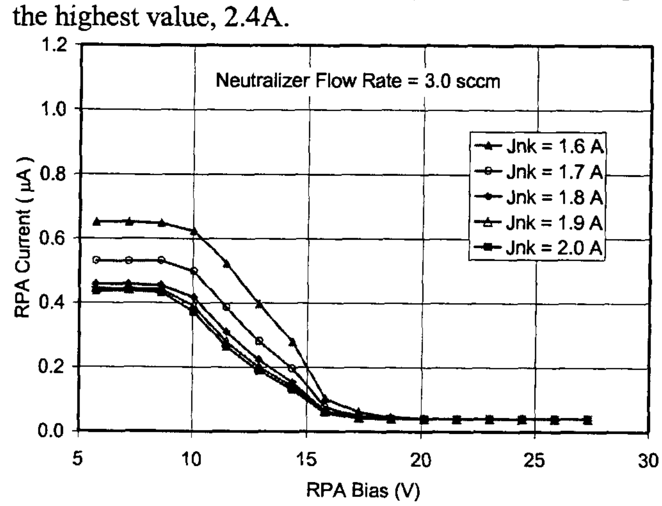

Fig. 9 PRA traces at neutralizer flow of 3.0 sccm.

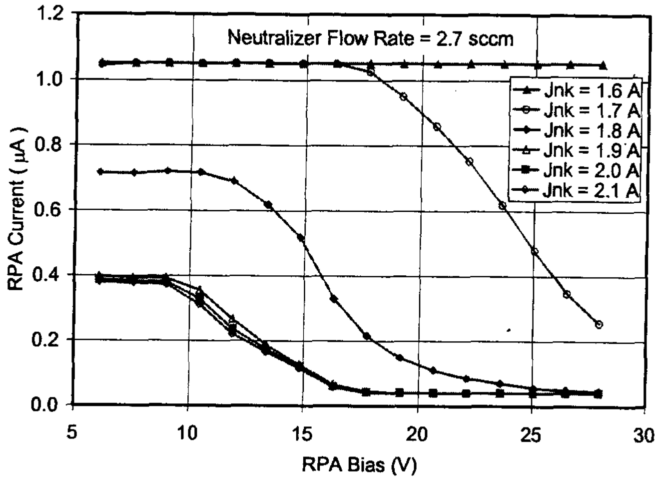

Fig. 10 PRA traces at neutralizer flow of 2.7 sccm.

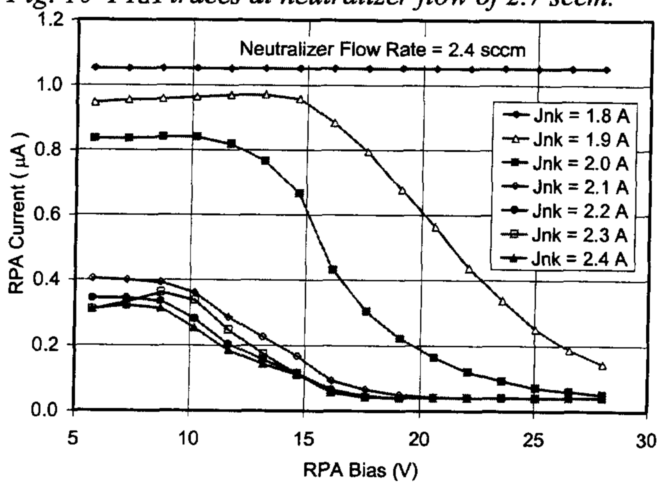

Fig. 11 PRA traces at neutralizer flow of 2.4 sccm.

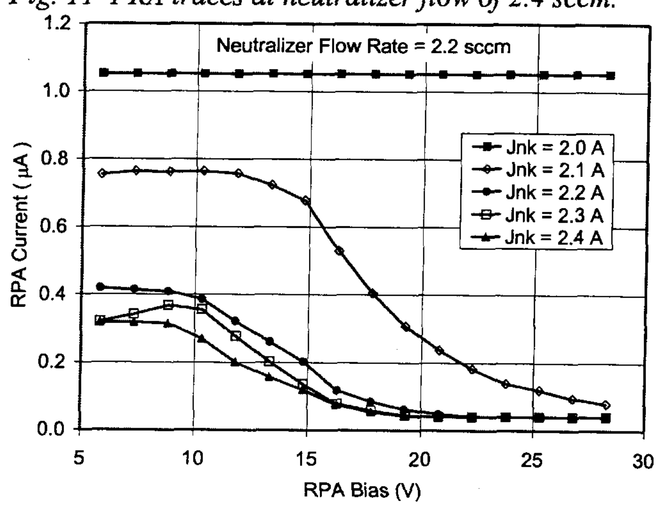

Fig. 12 PRA traces at neutralizer flow of 2.2 sccm.

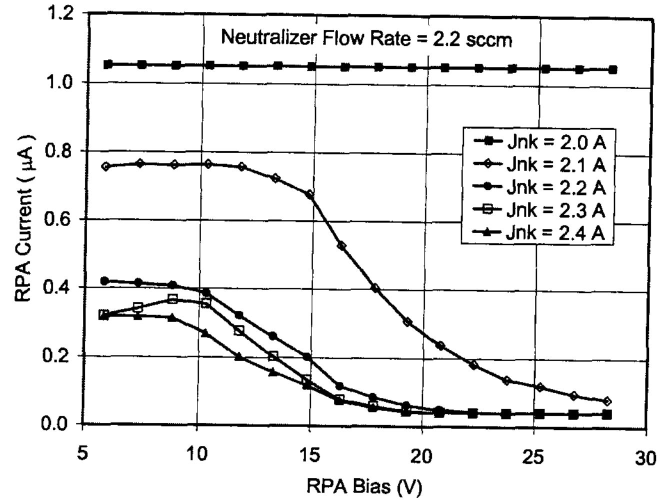

Fig. 13 PRA traces at neutralizer flow of 2.0 sccm.

The RPA data indicates that the existence of high energy ions during neutralizer operation in plume mode. These energetic ions may be expected to result in increased erosion of the neutralizer cathode shortening its life. Additional evidence for the existence of energetic ions comes from the PEPE (ref) instrument. During normal neutralizer operation PEPE sees a low energy ion distribution with a peak of around 10 eV and a width of a few eV. In plume mode operation on December 11 PEPE saw two ion distributions one at 10 eV +/-3 eV and the other at 50 eV +/-12 [Ref. Frank Crary at Univ. of Michigan].

The PMS was repeated using the DS1 flight spare ion thruster that is undergoing an Extended Life Test (ELT) at JPL. The instrumentation for the ELT includes the same RPA as on DS1 located in approximately the same position relative to the thruster. At the time the PMS was performed on the flight spare thruster it had been operated for XX,XXX hours and had processed approximately YYY kg of xenon. In contrast, at the time the first PMS was performed on DS1, the thruster had been operated for ZZ,ZZZ hours and had processed about AA kg of xenon. The much larger amount of xenon processed by the flight spare thruster in the ELT is due to the fact that it was operated at a much higher average power level than DS1. Of the ZZ,ZZZ hours of operating time for the flight spare thruster, KK,KKK hours were at full power (TH15), J,JJJ hours were at 2/3 of full power (TH8), and 500 hours were at TH12.

The results of the plume mode survey conducted on the flight spare thruster are given in Figs. 13-17. Qualitatively, these data show the same neutralizer behavior as the flight thruster. That is, the RPA data indicate that the neutralizer operation transitions to the plume mode as the neutralizer flow rate and keeper current are reduced.

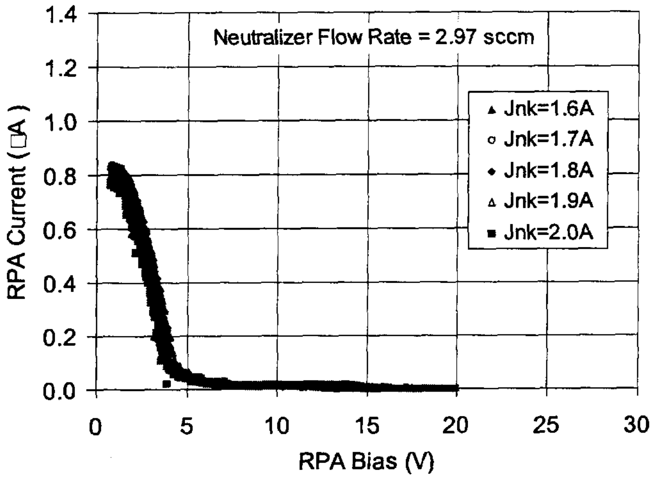

Fig. 13 RPA traces for the flight spare ion thruster with neutralizer flow rate = 3.0 sccm.

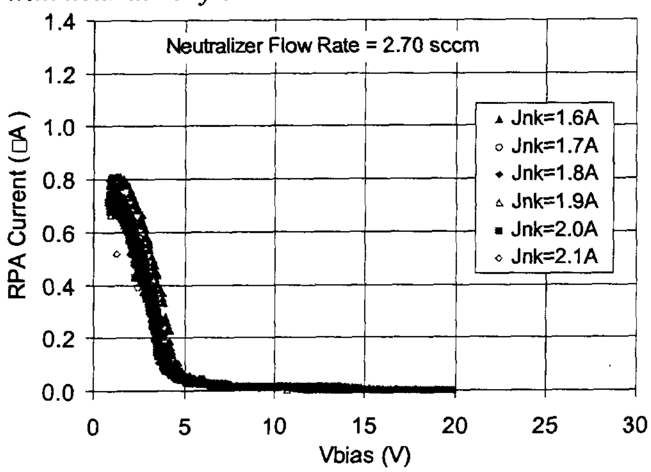

Fig. 14 RPA traces for the flight spare ion thruster with neutralizer flow rate = 2.7 sccm.

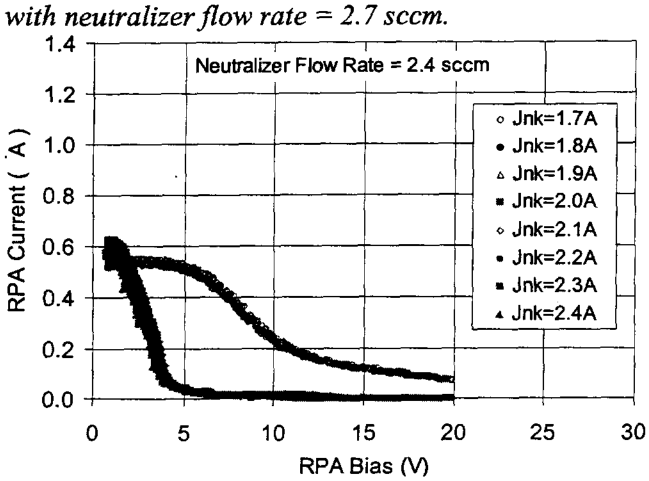

Fig. 15 RPA traces for the flight spare ion thruster with neutralizer flow rate = 2.4 sccm.

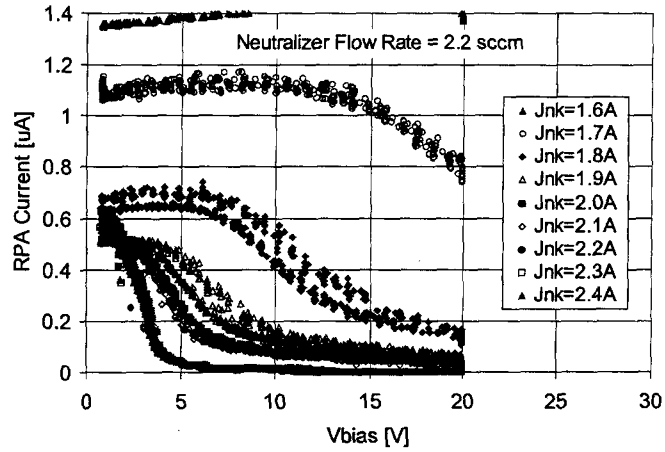

Fig. 16 RPA traces for the flight spare ion thruster with neutralizer flow rate = 2.2 sccm.

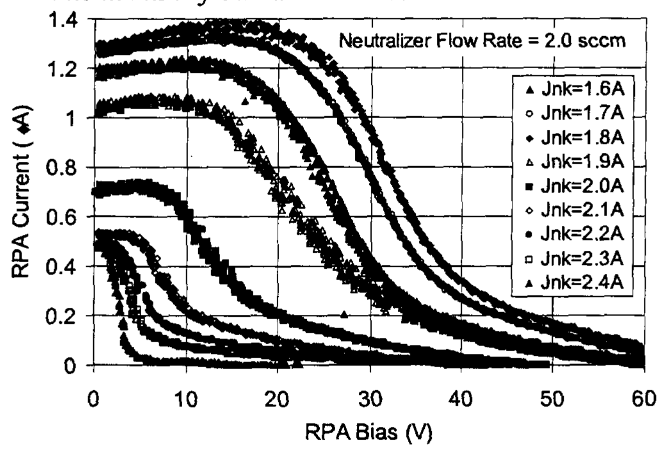

Fig. 17 RPA traces for the ground test of the flight spare ion thruster with neutralizer flow rate = 2.0 sccm.

The working definition for neutralizer plume mode is when the AC component of the neutralizer keeper voltage exceeds 5 volts peak-to-peak. Oscilloscope traces of the neutralizer keeper voltage indicate that this limit is exceeded when the RPA traces indicate that the neutralizer is in plume mode, i.e., "plume mode" as indicated by the RPA traces is consistent with plume mode identified by oscillations in the neutralizer keeper voltage exceeding 5 V peak-to-peak. These data provided the necessary confirmation that what was suspected to be plume mode operation for the neutralizer during the Extended Mission, was truly plume mode as it is normally defined.

The data in Figs. 13-17, however, indicate that the transition to plume mode occurs at different flow rate and keeper currents than on DS1. For example, at a neutralizer flow rate of 2.7 sccm, the flight data indicates a transition to plume mode at a keeper current of approximately 1.8 A. The ground test data from the flight spare thruster indicates no transition to plume mode at this flow rate even at keeper currents as low as 1.6 A. At 2.4 sccm the flight data shows a transition to plume mode at a keeper current of 2.0 A, but the ground test data shows this transition at 1.7 A.

There are two potentially significant differences between the flight and ground test conditions. First, the ground test environment is characterized by a much higher background pressure of xenon. The vacuum chamber pressure during these tests ranged between XX and YY Pa. Second, the flight thruster accumulated much of its operating time at the low power end of the NSTAR throttle range, whereas, the ground test thruster accumulated all of its operating time at the high power end of the throttling range.

The fact that the neutralizer characteristics on DS1 changed during the Extended Mission, requiring an increase in flow rate to keep it out of plume mode, suggests that extended operation at low power is "hard" on the neutralizer. After this experience, the operating point of the flight spare thruster in the ELT was changed to TH0 in an effort to look for evidence of neutralizer aging at lower power. As described by Sengupta, et al. [ref], extended operation at low power does appear to cause neutralizer degradation. This degradation manifests itself as an increase in neutralizer keeper voltage, similar to that observed on DS1. Along with this voltage increase is a decrease in the flow rate margin, which is defined as the difference between the throttle table flow rate and the flow rate at which the neutralizer transitions to plume mode. In the ELT, these changes are accompanied by a buildup of material in the neutralizer orifice [ref]. This deposition of material did not occur in the 8.2-khr Life Demonstration Test of the NSTAR thruster [ref]. Indeed, there was a net removal of material in the neutralizer orifice in this test, however, the thruster in the LDT was operated at full power for the entire test.

Therefore, it is quite likely that the NSTAR neutralizer exhibits net erosion after long-term operation at full power and net deposition at low power. Unfortunately, it is also quite likely that these erosion and deposition process do not occur at the same locations within the orifice. The erosion in the LDT occurred at the downstream end of the orifice and the deposits may occur primarily at the upstream end.

It is clear from comparing the data in Figs 9 through 17 that there is less flow rate margin for the neutralizer on DS1 than there is for the flight spare thruster in the ELT. The key unknown is whether this difference is a facility effect or a reflection of the different operating histories of the cathodes. If it is a facility effect, then a much better understanding of the neutralization process and neutralizer operation in space will be required to be able to establish the correct flow rates, keeper currents and margins. If it is a reflection of the cathode operating histories, then better models of the cathode wear are required.

Finally, the good news is that the data in Figs. 11-13 indicate that relatively small increases in the neutralizer keeper current are sufficient to drive the neutralizer operation out of plume mode. For example, at a neutralizer flow rate of 2.4 sccm, increasing the keeper current by 0.4 A (from 2.0 A to 2.4 A) will take the neutralizer out of plume mode and provide significant flow rate margin (since even at 2.0 sccm the neutralizer is not in plume mode with at keeper current of 2.4 A). The keeper voltage is about 18.5 V, so the increase in keeper current will require an additional 7.4 W. This is only 1.4 % of the end-of-life thruster input power at TH0.

Alternatively, the neutralizer flow rate could be increased to keep it out of plume mode, as was done on DS1. This, however, has a significantly larger impact on the thruster performance. This approach was acceptable for DS1 since there was more than enough propellant on board to complete the Extended Mission.

Perveance Margin

The results of the perveance tests at TH0 and TH3 are given in Figs. 18 and 19, respectively. For the NSTAR thruster the working definition of the perveance limit is where the slope of the accelerator grid current versus beam voltage has a slope of –0.02 mA/V. At TH0 and TH3 these data indicate perveance limits of 445 V and 491 V, respectively. The change in perveance limit with propellant throughput measured in the ELT [ref] is given in Fig. 20 for TH0 and TH3. While these perveance data were measured at the indicated throttle levels, the throughput was achieve by operating the thruster mainly at TH15 and TH8 as described in [ref]. The perveance limits measured on DS1 are indicated in Fig. 20, suggesting that the grids essentially like new and have experienced very little erosion.

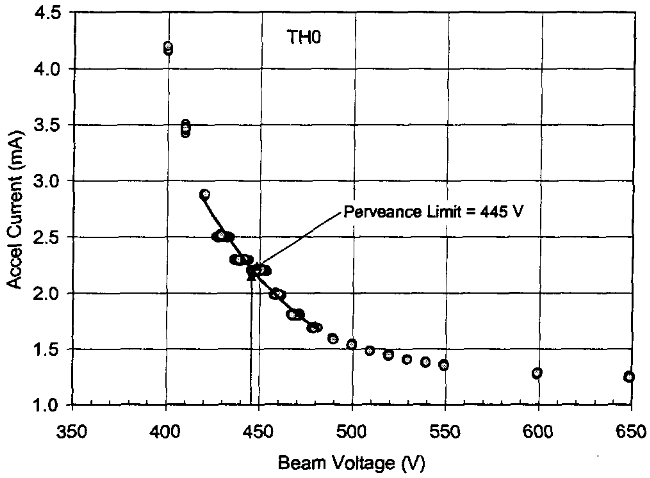

Fig. 18 Perveance data from DS1 at TH0.

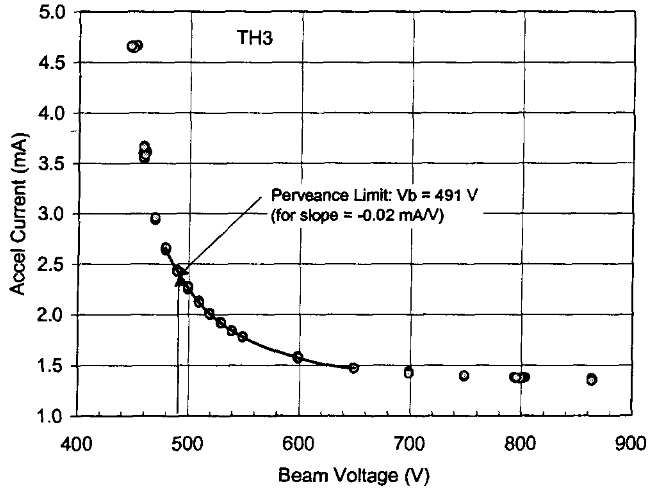

Fig. 19 Perveance datafrom DS1 TH3.

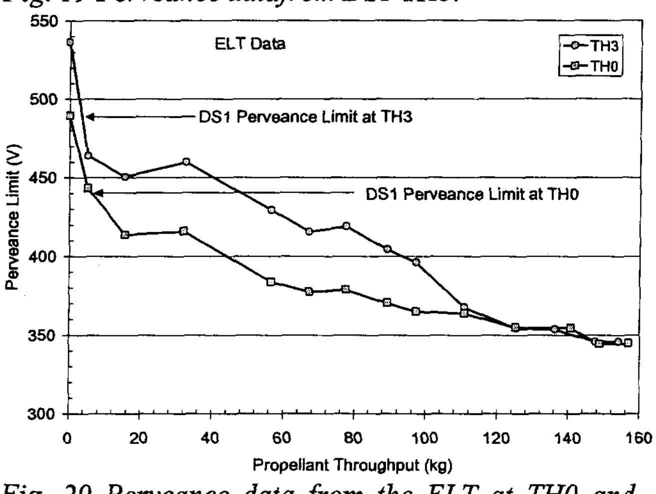

Fig. 20 Perveance data from the ELT at TH0 and TH3.

Electron-Backstreaming (EBS)

The perveance data from DS1 at TH0 and TH3 and the ELT were used to predict the electron-backstreaming voltage at TH0 on DS1. To do this the electon-backstreaming voltage from the ELT at TH0 is plotted against the perveance limits at TH0 and TH3 as shown in Fig. 21. The measured values of the perveance limits from DS1 are then used to find the corresponding the electron-backstreaming limit. Both perveance measurements predict an electron-backstreaming limit at TH0 of -71 V. The results of the electron-backstreaming measurement on DS1 at TH0 are shown in Fig. 22. These data indicate an EBS limit of -80 V. The variation in EBS voltage with throughput in the ELT for TH0 is given in Fig. 23. The EBS limit from DS1 is also indicated on this figure, suggesting that the grids are not "like new" and have experienced significant erosion.

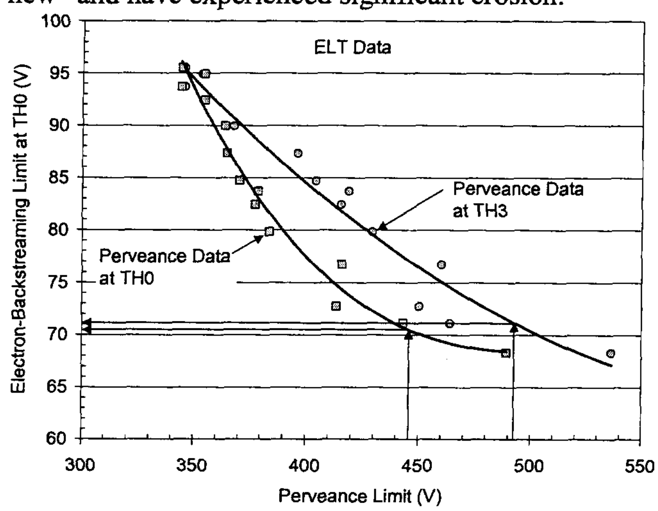

Fig. 21 Prediction of electron-backstreaming voltage on DS1 at TH0 using the measured perveance limits at TH0 and TH3 together with the measured variation in EBS voltage with perveance measured in the ELT.

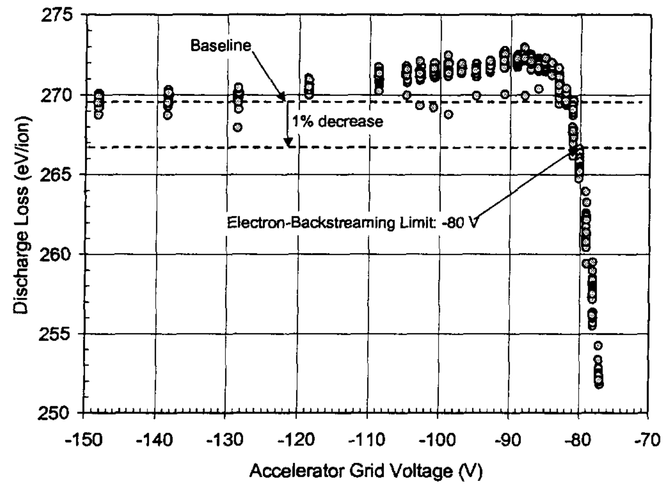

Fig. 22 Electron-backstreaming data from DS1 at TH0.

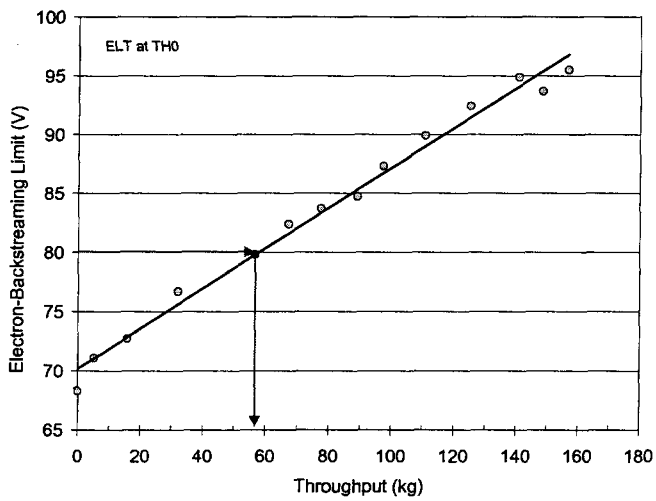

Fig. 23 Electron-backstreaming data from the ELT at TH0.

Future Work

Direct thrust measurements, discharge chamber performance curve measurements, solar array interaction, magnetic field measurements, single plenum operation, PEPE measurements, and ACS data are still being analyzed and will be presented at a later date.

Conclusions

The DS1 hyper-extended mission provided a unique opportunity to investigate the condition of the NSTAR ion thruster after long-term operation in space. At the end of the hyper-extended mission, the DS1 ion thruster had accumulated 16,265 kg of xenon and processed approximately 72 kg of xenon.

Data from the DS1 ion propulsion system diagnostics package clearly indicated that the neutralizer operation had transitioned to the undesirable plume-mode. This conclusion was subsequently supported by ground measurements on the DS1 flight spare thruster. An extensive mapping of the neutralizer characteristics during the hyper-extended mission identified the combinations of neutralizer flow rates and keeper currents at which the transition to plume mode occurs for operation at the thruster's minimum power point. Similar measurements made on the ground with the flight spare thruster exhibit similar qualitative behavior, but different values for the flow rates and currents at which the transitions to plume mode occur. It is not clear at this time if this difference is due to a facility effect resulting from the higher background pressure of xenon in the vacuum chamber, or if its due to the different operating histories of the flight and flight spare thrusters.

Perveance measurements made at two different power levels are consistent with there being very little erosion of the accelerator grid apertures. However, the measurement of electron-backstreaming made at the thruster's minimum power point is more consistent with significant erosion of the grid apertures. The resolution of this difference is still being worked.

Acknowledgements

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Table 1 End-of-Life flight throttle table of parameters used in mission analysis.

Throttle Level	Mission Level	PPU Input Power (W)	Thruster Input Power (W)	Thrust (mN)	Specific Impulse (s)	Thruster Efficiency	Main Flow Rate (sccm)	Cathode Flow Rate (sccm)	Neutralizer Flow Rate (sccm)
15	**111**	**2567**	**2325**	**92.70**	**3127**	**0.612**	**23.43**	**3.70**	**3.59**
	110	2546	2308	92.20	3113	0.610	23.43	3.70	3.59
	109	2525	2291	91.80	3099	0.609	23.43	3.70	3.59
	108	2505	2274	91.40	3084	0.608	23.43	3.70	3.59
	107	2484	2257	91.00	3069	0.607	23.43	3.70	3.59
	106	2464	2240	90.50	3055	0.605	23.43	3.70	3.59
	105	2443	2223	90.10	3040	0.604	23.43	3.70	3.59
14	**104**	**2416**	**2200**	**87.90**	**3164**	**0.620**	**22.19**	**3.35**	**3.25**
	103	2394	2182	87.40	3148	0.618	22.19	3.35	3.25
	102	2373	2164	87.00	3132	0.618	22.19	3.35	3.25
	101	2353	2147	86.50	3116	0.616	22.19	3.35	3.25
	100	2332	2129	86.10	3099	0.615	22.19	3.35	3.25
	99	2311	2111	85.60	3083	0.613	22.19	3.35	3.25
	98	2290	2093	85.20	3066	0.612	22.19	3.35	3.25
13	**97**	**2271**	**2077**	**83.10**	**3192**	**0.626**	**20.95**	**3.06**	**2.97**
	96	2251	2060	82.70	3176	0.625	20.95	3.06	2.97
	95	2233	2044	82.20	3160	0.623	20.95	3.06	2.97
	94	2213	2027	81.80	3143	0.622	20.95	3.06	2.97
	93	2193	2010	81.40	3127	0.621	20.95	3.06	2.97
	92	2174	1993	81.00	3110	0.620	20.95	3.06	2.97
	91	2154	1976	80.50	3094	0.618	20.95	3.06	2.97
12	**90**	**2136**	**1960**	**78.40**	**3181**	**0.624**	**19.86**	**2.89**	**2.80**
	89	2118	1944	78.00	3164	0.623	19.86	2.89	2.80
	88	2100	1928	77.60	3148	0.621	19.86	2.89	2.80
	87	2081	1912	77.20	3132	0.620	19.86	2.89	2.80
	86	2063	1896	76.80	3116	0.619	19.86	2.89	2.80
	85	2045	1880	76.40	3099	0.618	19.86	2.89	2.80
	84	2027	1864	76.00	3083	0.617	19.86	2.89	2.80
11	**83**	**2006**	**1845**	**73.60**	**3196**	**0.625**	**18.51**	**2.72**	**2.64**
	82	1986	1827	73.20	3177	0.624	18.51	2.72	2.64
	81	1965	1809	72.70	3157	0.622	18.51	2.72	2.64
	80	1945	1791	72.30	3138	0.621	18.51	2.72	2.64
	79	1925	1773	71.80	3118	0.619	18.51	2.72	2.64
	78	1906	1756	71.40	3099	0.618	18.51	2.72	2.64
	77	1886	1738	70.90	3079	0.616	18.51	2.72	2.64
10	**76**	**1863**	**1717**	**68.40**	**3184**	**0.622**	**17.22**	**2.56**	**2.48**
	75	1842	1698	67.90	3162	0.620	17.22	2.56	2.48
	74	1820	1678	67.40	3140	0.619	17.22	2.56	2.48
	73	1799	1659	66.90	3117	0.617	17.22	2.56	2.48
	72	1778	1640	66.50	3095	0.616	17.22	2.56	2.48
	71	1758	1621	66.00	3072	0.614	17.22	2.56	2.48
	70	1737	1602	65.50	3049	0.611	17.22	2.56	2.48
9	**69**	**1712**	**1579**	**63.20**	**3142**	**0.617**	**15.98**	**2.47**	**2.39**
	68	1693	1562	62.70	3121	0.614	15.98	2.47	2.39
	67	1674	1544	62.30	3099	0.613	15.98	2.47	2.39
	66	1654	1526	61.80	3077	0.611	15.98	2.47	2.39
	65	1636	1509	61.40	3055	0.610	15.98	2.47	2.39

Throttle Level	Mission Level	PPU Input Power (W)	Thruster Input Power (W)	Thrust (mN)	Specific Impulse (s)	Thruster Efficiency	Main Flow Rate (sccm)	Cathode Flow Rate (sccm)	Neutralizer Flow Rate (sccm)
	64	1616	1491	61.00	3032	0.608	15.98	2.47	2.39
	63	1597	1473	60.50	3010	0.606	15.98	2.47	2.39
8	**62**	**1578**	**1456**	**57.90**	**3115**	**0.608**	**14.41**	**2.47**	**2.39**
	61	1561	1440	57.50	3093	0.606	14.41	2.47	2.39
	60	1544	1424	57.10	3071	0.604	14.41	2.47	2.39
	59	1527	1408	56.70	3050	0.602	14.41	2.47	2.39
	58	1508	1391	56.30	3028	0.601	14.41	2.47	2.39
	57	1491	1375	55.90	3005	0.599	14.41	2.47	2.39
	56	1474	1359	55.40	2983	0.596	14.41	2.47	2.39
7	**55**	**1458**	**1344**	**52.70**	**3074**	**0.591**	**12.90**	**2.47**	**2.39**
	54	1442	1329	52.30	3053	0.589	12.90	2.47	2.39
	53	1426	1314	51.90	3032	0.587	12.90	2.47	2.39
	52	1411	1300	51.60	3010	0.586	12.90	2.47	2.39
	51	1395	1285	51.20	2988	0.584	12.90	2.47	2.39
	50	1379	1270	50.80	2966	0.582	12.90	2.47	2.39
	49	1364	1256	50.40	2944	0.579	12.90	2.47	2.39
6	**48**	**1345**	**1238**	**47.90**	**3065**	**0.582**	**11.33**	**2.47**	**2.39**
	47	1328	1222	47.50	3040	0.580	11.33	2.47	2.39
	46	1311	1206	47.10	3014	0.577	11.33	2.47	2.39
	45	1294	1190	46.70	2988	0.575	11.33	2.47	2.39
	44	1277	1174	46.30	2962	0.573	11.33	2.47	2.39
	43	1260	1158	45.80	2936	0.570	11.33	2.47	2.39
	42	1243	1142	45.40	2909	0.567	11.33	2.47	2.39
5	**41**	**1222**	**1123**	**42.60**	**3009**	**0.560**	**9.82**	**2.47**	**2.39**
	40	1207	1108	42.20	2983	0.557	9.82	2.47	2.39
	39	1191	1093	41.90	2956	0.556	9.82	2.47	2.39
	38	1175	1078	41.50	2929	0.553	9.82	2.47	2.39
	37	1159	1063	41.10	2902	0.550	9.82	2.47	2.39
	36	1143	1048	40.70	2875	0.548	9.82	2.47	2.39
	35	1127	1033	40.30	2847	0.545	9.82	2.47	2.39
4	**34**	**1111**	**1018**	**37.40**	**2942**	**0.530**	**8.30**	**2.47**	**2.39**
	33	1094	1002	37.00	2911	0.527	8.30	2.47	2.39
	32	1077	986	36.60	2879	0.524	8.30	2.47	2.39
	31	1061	971	36.20	2847	0.521	8.30	2.47	2.39
	30	1044	955	35.70	2815	0.516	8.30	2.47	2.39
	29	1027	939	35.30	2782	0.513	8.30	2.47	2.39
	28	1010	923	34.90	2749	0.510	8.30	2.47	2.39
3	**27**	**994**	**908**	**32.10**	**2843**	**0.493**	**6.85**	**2.47**	**2.39**
	26	970	885	31.50	2792	0.487	6.85	2.47	2.39
	25	946	862	30.90	2739	0.482	6.85	2.47	2.39
	24	922	840	30.30	2686	0.475	6.85	2.47	2.39
	23	898	817	29.70	2631	0.469	6.85	2.47	2.39
	22	873	794	29.10	2576	0.463	6.85	2.47	2.39
	21	850	772	28.50	2519	0.456	6.85	2.47	2.39
2	**20**	**825**	**749**	**27.50**	**2678**	**0.482**	**5.77**	**2.47**	**2.39**
	19	811	736	27.10	2646	0.478	5.77	2.47	2.39
	18	799	724	26.80	2613	0.474	5.77	2.47	2.39
	17	785	711	26.50	2580	0.472	5.77	2.47	2.39

[illegible]	[illegible]	[illegible] Power [illegible]	Thruster Input Power	Thrust (mN)	Specific Impulse (s)	Thruster Efficiency	Main Flow Rate (sccm)	Cathode Flow Rate (sccm)	Neutralizer Flow Rate (sccm)
	16	771	698	26.10	2547	0.467	5.77	2.47	2.39
	15	757	685	25.80	2513	0.464	5.77	2.47	2.39
	14	743	672	25.40	2479	0.460	5.77	2.47	2.39
1	**13**	**729**	**659**	**24.60**	**2382**	**0.436**	**5.82**	**2.47**	**2.39**
	12	708	639	24.00	2325	0.428	5.82	2.47	2.39
	11	686	619	23.40	2266	0.420	5.82	2.47	2.39
	10	665	599	22.70	2206	0.410	5.82	2.47	2.39
	9	643	579	22.10	2143	0.401	5.82	2.47	2.39
	8	622	559	21.40	2079	0.390	5.82	2.47	2.39
	7	600	539	20.70	2013	0.379	5.82	2.47	2.39
0	**6**	**577**	**518**	**20.70**	**1979**	**0.388**	**5.98**	**2.47**	**2.39**
	5	569	510	20.40	1952	0.383	5.98	2.47	2.39
	4	560	502	20.10	1925	0.378	5.98	2.47	2.39
	3	551	494	19.90	1898	0.375	5.98	2.47	2.39
	2	542	485	19.60	1870	0.371	5.98	2.47	2.39
	1	533	477	19.30	1842	0.366	5.98	2.47	2.39
	0	524	469	19.00	1814	0.360	5.98	2.47	2.39

Table 2 Summary of Tests Performed in the Hyper-Extended Mission.

Test Name	Start	Finish	Comment
Plume Mode Survey	2001-296/11:30:00	2001-296/23:15:00	Test terminated onboard by Neutralizer Keeper overvoltage trip (Vnk>20 V)
Ion Optics Test	2001-310/10:00:00	2001-310/16:00:00	Incorrect parameter used to compute beam voltage resulted in early termination of test
XFS Solenoid Valve Setup	2001-310/18:00:00	2001-310/18:15:00	Reduce hold time for solenoid valves from 12 seconds to 2 seconds
ML27 Test	2001-310/18:30:00	2001-310/19:30:00	Verify fast XFS pressurization, Assess DS1 power system ability to support high thrust levels in IAT3
Perveance	2001-316/21:45	2001-317/01:30	
Backstream	2001-317/05:30	2001-317/06:30	
IAT3+	2001-323/08:00:00	2001-324/09:00:00	Doppler-measured thrust, high-thrust, low impulse, ion optics – terminated by DS1 battery SOC fault protect
IAT3 R	2001-336/18:12:00	2001-336/	
Plume Mode Survey #2	2001-344/14:26:00	2001-345/13:10:00	
Low Flow #2	2001-347/09:55:00	2001-348/00:32:00	
Diode Mode	2001-352		Successful diode mode just before they pulled the plug